Space-based estimate of the volcanic heat flux into the atmosphere during 2001 and 2002

Robert Wright*
Luke P. Flynn
Hawai'i Institute of Geophysics and Planetology, University of Hawaii, 2525 Correa Road, Honolulu, Hawaii 96822, USA

ABSTRACT

Satellite remote sensing offers a convenient way to monitor changes in the thermal budgets of Earth's subaerially active volcanoes. By using data acquired by the National Aeronautics and Space Administration's Moderate Resolution Imaging Spectro-radiometer, we have calculated the amount of heat released into the atmosphere by 45 volcanoes active during 2001 and 2002, in order to quantify the contribution active volcanism makes to Earth's energy budget. We report that the amount of heat radiated into the troposphere by these volcanoes, as detected from space, was ~5.34 × 10^{16} and 5.30 × 10^{16} J/yr during 2001 and 2002, respectively. This energy flux is three orders of magnitude less than the amount of energy consumed by the United States of America for residential, manufacturing, and transportation purposes during 1999.

Keywords: volcanoes, remote sensing, thermal emission, mass balance.

INTRODUCTION

During the 1990s an average of 60 volcanoes erupted each year, ~20 of which were erupting on any given day (Simkin and Siebert, 2000). Some of these, such as Erta Ale in Ethiopia, are persistently active, whereas others, such as Pacaya in Guatemala, erupt more sporadically. Satellite remote sensing offers the possibility to document quantitatively the amount of thermal energy released from all of Earth's subaerially active volcanoes in a systematic way (Glaze et al., 1989). By using data from Earth-orbiting satellites, several studies have documented the radiant flux from individual volcanoes and have used this information to characterize eruptive behavior and identify eruptive patterns (e.g., Oppenheimer et al., 1993; Wright et al., 2002a). However, such studies have often been experimental and intermittent or, when carried out in a more systematic manner (e.g., Dehn et al., 2000), restricted to particular areas of the globe. As a result, a complete inventory of the global volcanic heat flux into the atmosphere has yet to be obtained.

The MODVOLC algorithm (Wright et al., 2002b) uses data from the National Aeronautics and Space Administration's Terra Moderate Resolution Imaging Spectro-radiometer (MODIS) sensor to detect and map the global distribution of volcanic surface thermal anomalies in near-real time (http://modis.higp.hawaii.edu). Through the use of this system we have estimated the total amount of thermal energy released into Earth's atmosphere by 45 volcanoes identified as being in a state of thermal unrest during 2001 and 2002 (Fig. 1; Table 1).

*E-mail: wright@higp.hawaii.edu.

METHOD

For each MODIS pixel identified as containing a volcanic heat source (Fig. 1, inset), the algorithm reports the date and time of observation, the geographic location, the satellite observation geometry, and the spectral radiance emitted by the pixel in five spectral wavebands.

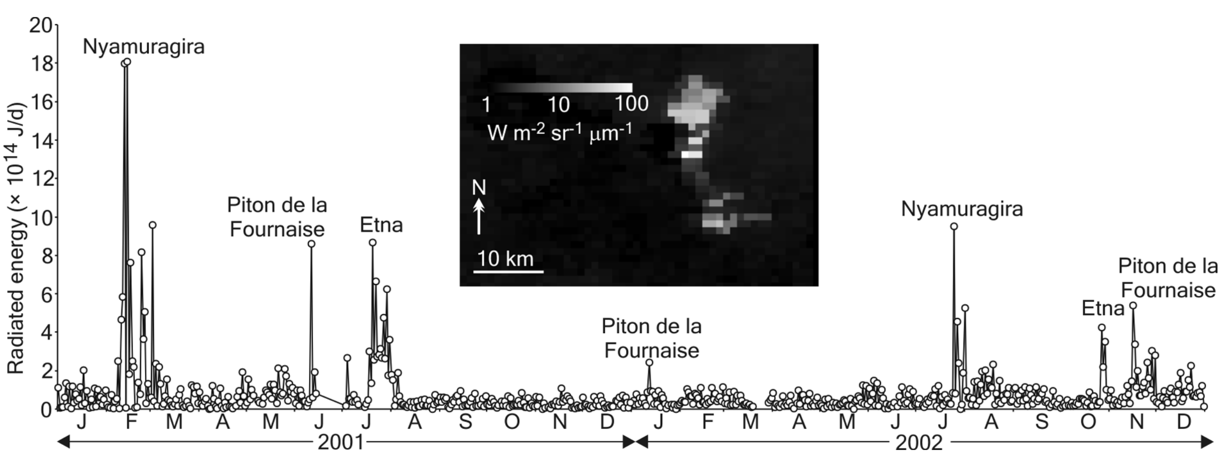

Figure 1. Daily variation in total heat radiated from 45 active volcanoes listed in Table 1, during 2001 and 2002. Months abbreviated on *x* axis. Inset: Subset of MODIS 3.959 μm image (band 21), acquired on night of 10 February 2001, of lava flow eruption at Nyamuragira volcano, Democratic Republic of Congo. Bright pixels contain active lava flows, presence of which elevates emitted 3.959 μm spectral radiance substantially above that recorded for adjacent image pixels that do not contain active lava. MODVOLC algorithm automatically detects such hot-spot pixels.

TABLE 1. HEAT RADIATED BY 45 VOLCANOES ACTIVE DURING 2001 AND 2002 ($\times 10^{15}$ J/yr)

Volcano	2001	2002	Volcano	2001	2002	Volcano	2001	2002
Ambrym	1.26	3.14	Karymsky	*	1.33	Piton de la Fournaise	1.71	2.47
Arenal	0.37	0.23	Kavachi	*	0.03	Popocatépetl	0.71	0.79
Bagana	0.62	0.92	Kīlauea	13.00	12.20	Rabaul	0.36	0.29
Belinda	0.06	0.91	Krakatau	0.27	*	Reventador	*	0.18
Bezymianny	0.33	0.02	Langila	*	0.32	Santiaguito	1.09	0.95
Big Ben	0.01	*	Láscar	0.44	0.52	Semeru	0.72	1.10
Cleveland	0.07	*	Lopevi	0.16	*	Shiveluch	2.08	2.64
Colima	*	0.97	Manam	*	0.34	Soufrière Hills	1.80	3.87
Dukono	*	0.07	Mayon	0.30	*	Stromboli	*	0.47
Erebus	0.60	0.68	Merapi	2.13	0.49	Suwanose Jima	*	0.01
Erta ʻAle	2.24	2.47	Michael	0.37	0.55	Tinakula	0.16	*
Etna	7.93	3.60	Nyamuragira	13.30	4.68	Tungurahua	*	0.63
Fuego	*	2.74	Nyiragongo	*	1.71	Ulawun	0.09	*
Ibu	0.20	*	Pacaya	0.01	*	Villarrica	0.06	*
Karangetang	0.78	0.14	Pago	*	1.11	Yasur	0.20	0.77

*No thermal activity detected by the MODVOLC algorithm during this year.

The spectral radiance emitted by the hot-spot pixel at 3.959 μm can be converted to an estimate of radiative power loss from that pixel (E_f in MW) by using the following approximation (Kaufman et al., 1998):

$$E_f = 4.34 \times 10^{-19}(T_{4h}^8 - T_{4b}^8). \qquad (1)$$

Here, T_{4h} (in K) is obtained by converting the measured 3.959 μm hot-spot pixel radiance value to temperature, T, by using Planck's blackbody radiation law, and T_{4b} is the temperature of the ground surrounding the volcanic heat source obtained from pixels surrounding the hot-spot pixel.

Equation 1 was developed to determine radiative power output from vegetation fires and is a best fit to many thousands of hypothetical subpixel surface-temperature distributions (i.e., flaming and smoldering fires covering varying amounts of the 1 km MODIS image pixel). However, the temperature distributions upon which equation 1 is based are directly analogous to the observed surface-temperature distributions of active lava features, whereby lavas of varying ages, and hence temperatures, cover varying proportions of the image pixel.

We calculated E_f for each hot-spot pixel, on each day, for each volcano listed in Table 1. T_{4h} was obtained primarily by using band 22, which has a higher radiometric precision than band 21 (0.07 K and 2.0 K, respectively). However, when the emitted radiance exceeded the upper measurement limit of the band 22 detectors, band 21 data were used. Band 21 has a much larger radiometric range (to 500 K; cf. ~340 K for band 22).

Although Kaufman et al. (1998) calculated T_{4b} from the 3.959 μm radiance emitted by pixels surrounding the hot-spot pixel, MODVOLC only records the spectral radiance emitted by the hot-spot pixels. However, it can be shown (Wright et al., 2002b) that the band 32 (12.02 μm) temperature of the hot-spot pixel, which MODVOLC records, can be used as a proxy for T_{4b}. For example, a thermally homogeneous 1 km MODIS pixel radiating at 300 K emits 0.4 and 9.5 $W \cdot m^{-2} \cdot sr^{-1} \cdot \mu m^{-1}$ at 3.959 and 12.02 μm, respectively. However, whereas an active lava body radiating at 850 K and occupying 0.05% of this pixel causes the emitted radiance to increase by >200% at 3.959 μm, emission at 12.02 μm increases by <1%. Thus, the band 32 radiance emitted by the hot-spot pixel can be used to obtain a proxy for T_{4b} if the subpixel-sized hot spot is small. As the size of the volcanic hot spot within the pixel increases, this assumption becomes less valid. Thus, we used the lowest temperature recorded by band 32 at each volcano during each month, which represents the least hot-spot–contaminated band 32 temperature in the data set and compensates for seasonal variations in background temperature. We only considered hot spots observed at night, as these observations are uncontaminated by solar-reflection and solar-heating effects.

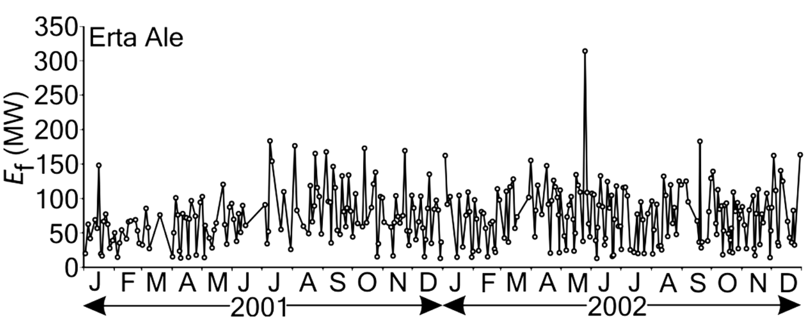

Figure 2. Radiative power loss from Erta ʻAle's lava lake during 2001 and 2002.

To assess the accuracy of equation 1 we can compare in situ estimates of E_f made at Erta Ale volcano with estimates made from the MODIS hot-spot data and the methods described herein. Field measurements of lava-lake area and surface temperature in February 2001 (Oppenheimer and Yirgu, 2002) indicate radiative heat losses in the range 74–152 MW, consistent with those calculated from the MODVOLC data by using equation 1 (Fig. 2). The range of E_f that we calculate for Erta Ale during 2001 and 2002 (13–330 MW) is also consistent with that calculated by others (11–400 MW) from thermal analysis of high-spatial-resolution Landsat Thematic Mapper satellite data using different methods (Glaze et al., 1989; Oppenheimer and Francis, 1997; Harris et al., 1999).

For lava bodies that occupied more than one MODIS image pixel, E_f was summed for each pixel to give the total radiated power in MW at the moment of MODIS overpass. Assuming this to be the average value for that particular day, we obtained the radiative energy loss in J/d (d = day). We then numerically integrated this energy flux with respect to time (by using trapezoidal summation) to determine the total energy emitted by each volcano in each of the two years (data presented in J/yr; Table 1).

RESULTS AND DISCUSSION

Figure 3 shows how the thermal budgets of four volcanoes with contrasting eruption styles varied during 2001, calculated by using equation 1 and the methods described herein. Erebus, Antarctica, and Kīlauea, Hawaii, are both, at present, persistently active, although the amount of heat radiated varies greatly. At Erebus, thermal emission is restricted to that from a lava lake 5–15 m in diameter (Aster et al., 2003), whereas activity at Kīlauea comprises the emplacement of numerous pāhoehoe lava flows from the active Puʻu ʻŌʻō vent, over an area of several square kilometers. The persistent nature of the activity at both of these volcanoes is reflected in the long-term thermal budgets, whereby short-term variations in radiated energy are superimposed on a more stable base line. These thermal budgets contrast markedly with those observed at Mount Etna, Sicily, and Popocatépetl, Mexico. Activity at Etna is characterized by prolonged periods of summit-crater activity on which are superimposed more voluminous effusive flank eruptions. Variations in power output detected from space during 2001 constitute a perfect example of this, whereby low levels of emitted energy produced by Strombolian eruptions and small lava flows at the summit increased

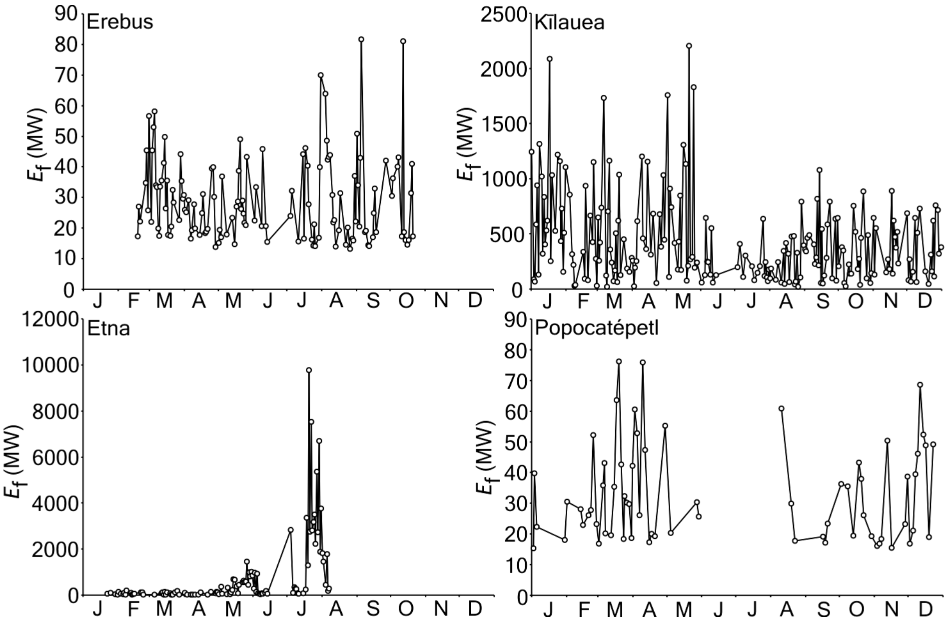

Figure 3. Radiative power loss from Erebus, Kīlauea, Etna, and Popocatépetl during 2001. Note different scales of ordinates. As we only use nighttime data in our analysis, data gaps exist between late October and mid-February at Erebus, during Antarctic summer.

gradually until 13 July 2001, when lava flows to 5 km long erupted from the southern flank of the volcano. Activity at lava dome–forming volcanoes can be distinctly cyclic (Denliger and Hoblitt, 1999), and since its reactivation in 1994, activity at Popocatépetl has been characterized by cycles of growth, and then explosive destruction, of at least 10 dacitic lava domes. Two of these cycles are depicted in Figure 3.

The total amount of heat radiated by the 45 actively erupting volcanoes detected by MODVOLC during 2001 and 2002 was 5.34 $\times$ 10^{16} and 5.30 $\times$ 10^{16} J/yr, respectively. Although the base-line level of radiative energy output is fairly constant over the 2 yr period, at a level below ~8 $\times$ 10^{13} J/d, individual effusive eruptions have a substantial impact on the overall pattern of thermal emission (Fig. 1). In 2001, eruptions at Nyamuragira, Democratic Republic of Congo, in March, and Etna, in July and August, radiated almost as much energy into the atmosphere (~40% of the total) as the other 30 volcanoes combined (Table 1). Similarly in 2002, the July eruption of Nyamuragira, the two eruptions of Piton de la Fournaise, Réunion Island, in January and November, and the prolonged flank eruption at Mount Etna that began on 26 October and continued into 2003, are conspicuous (Fig. 1).

These eruptions all involved the emplacement of extensive (5–20 km long) ‘a‘ā basaltic lava flows. The ‘a‘ā morphological type often advances as a single unit of lava encased within a continuously rupturing outer crust. Although lava is a relatively poor conductor, the cracks in this crust allow heat from the flow interior (which is close to the lava's eruption temperature) to be lost at a high rate. This is in contrast to pāhoehoe lavas, which lose heat at a lower rate during emplacement due to their relatively undisrupted, and insulating, outer skins. For example, the ‘a‘ā lava flows emplaced during the March 2001 eruption of Nyamuragira radiated more energy in 35 d (1.33 $\times$ 10^{16} J) than the pāhoehoe flows erupted at Kīlauea did during the entire year (1.30 $\times$ 10^{16} J). To place this in a historical context, it is estimated that the famous 1783 fissure eruption of Laki, Iceland, released ~5 $\times$ 10^{20} J of thermal energy during 8 months of effusive activity (Pyle, 2000).

Comparisons can also be made between volcanoes characterized by other eruption styles. During 2001 and 2002 the lava dome growing at Soufrière Hills volcano, Montserrat, radiated substantially more heat than the Santiaguito dome, which has been active at Santa Maria volcano, Guatemala, since 1922. This difference can be attributed to a combination of generally higher lava eruption rates at Soufrière Hills (in the range 0.5–11 $m^3 \cdot s^{-1}$ since 1995 [Watts et al., 2002]; cf. ~0.2–2.1 $m^3 \cdot s^{-1}$ at Santiaguito [Rose, 1987]), and a difference in emplacement style, which has been historically endogenous at Santiaguito (Rose, 1987), but both endogenous and exogenous at Soufrière Hills (Watts et al., 2002).

These heat-loss estimates ignore the contribution made by convection. Even when measurements of lava surface temperature can be made, heat loss via convection is difficult to constrain as it depends heavily on the prevailing wind speed and surface roughness, which are invariably unknown. However, theoretical (Head and Wilson, 1986; Neri, 1998) and empirical (Oppenheimer and Yirgu, 2002; Wooster et al., 1997) studies indicate that convective heat loss from active lava bodies may be equivalent to between 30% and 75% of the corresponding radiative power loss. By using this multiplication factor, the total volcanic heat-energy input (radiative and convective) into the atmosphere from the volcanoes listed in Table 1 may have been as high as ~9.0 $\times$ 10^{16} J in both 2001 and 2002.

Quantifying the thermal budget of a volcano can provide insights into how some, such as Erta Ale, can remain persistently active in terms of volatile and thermal emissions while erupting relatively little lava (Oppenheimer and Francis, 1997). Following Francis et al. (1993), we assume that the magma that cools to produce the measured surface heat flux becomes thermally isolated from the remaining melt and is emplaced either as dikes (model 1) or cumulates (model 2). The mass of magma needed to balance thermal losses is given by $Q/(L\Delta f + c\Delta T)$, where Q is heat loss (J), L is latent heat of crystallization (4.2 $\times$ 10^5 $J \cdot kg^{-1}$), and c is specific heat capacity (1.0 $\times$ 10^3 $J \cdot kg^{-1} \cdot K^{-1}$). The ΔT (cooling interval) and Δf (mass fraction of crystallization) vary by model and have respective values of 50 °C and 0.25 (model 1; dikes) and 400 °C and 1.0 (model 2; cumulates). By using this model, our data indicate that, during 2001, the amount of magma needed to balance the estimated thermal loss of 3.9 $\times$ 10^{15} J from the lava lake at Erta Ale (Table 1, including convective heat flux at 75% of radiative heat losses) was 2.6 $\times$ 10^{10} kg, if emplaced within the edifice as dikes, or 4.8 $\times$ 10^9 kg, if cooled and crystallized to a greater degree and emplaced as cumulates at an average rate of between 150 and 800 $kg \cdot s^{-1}$. Assuming a magma density of 2700 kg/m^3, this implies that a volume of between 2 and 10 $\times$ 10^6 m^3 of magma moved through the system during 2001.

Volcanic thermal emissions constitute a direct flux of heat into Earth's atmosphere. For purposes of comparison, anthropogenic thermal pollution can be estimated from energy-use statistics (i.e., that energy used for lighting, space heating, manufacturing, and transportation) by assuming that all energy consumed is eventually converted to heat. The total amount of volcanic heat energy released into the atmosphere in each of our study years (~9 $\times$ 10^{16} J) is more than 3 orders of magnitude less than the 1.01 $\times$ 10^{20} J of energy consumed by the United States in 1999 (Energy Information Administration, 2001). Alternatively, from our geographic perspective, the amount of heat energy released by Kīlauea volcano in each of these years (~2.28×10^{16} and 2.22×10^{16} J) is almost equivalent to the total amount of energy consumed for residential purposes in the state of Hawaii during 1999 (2.42×10^{16} J).

The heat-loss estimates we report are minimum estimates. Some volcanoes characterized by levels of activity, such as persistent degassing or fumarolic activity, that fall below the sensitivity limit of our algorithm (see Wright et al., 2002b, for details) also liberate a quantity of heat that is not included in our estimates. Although no Plinian eruptions have occurred during the period we consider, quantifying the thermal energy released during the climactic phases of such an eruption would also be unamenable to the techniques we describe because of their relatively short duration and the fact that most of the thermal energy is transferred by the rapidly cooling plume.

CONCLUSIONS

Our results indicate a steady-state level of volcanic heat input to the troposphere during 2001 and 2002, superimposed on which are relatively large spikes attributable to large individual, and basaltic, effusive eruptions. The 1×10^{18} J of thermal energy estimated to have been released into the atmosphere by the 18 May 1980 eruption of Mount St. Helens (Pyle, 2000) further illustrates how brief and relatively infrequent explosive eruptions may enhance the longer-term volcanic heat fluxes we present here. We look forward to extending our current MODIS inventory, and mining archival satellite data sets, to compile a more extensive temporal baseline of global volcanic energy output. An extended inventory, perhaps spanning 15–20 yr, will allow us to search for statistically significant variability in the baseline energy flux of all of Earth's active volcanoes.

ACKNOWLEDGMENTS

Funded by the Hawai'i Space Grant Consortium (NASA grant NGT5-40076). We thank Eric Pilger for maintaining the MODIS hot-spots database and L. Glaze and C. Oppenheimer for reviewing the paper. Hawai'i Institute of Geophysics and Planetology publication 1314 and School of Ocean, Earth Science and Technology publication 6307.

REFERENCES CITED

Aster, R., Mah, S., Kyle, P., McIntosh, W., Dunbar, M., Johnson, J., Ruiz, M., and McNamara, S., 2003, Very long period oscillations of Mount Erebus Volcano: Journal of Geophysical Research, v. 108, no. B11, doi: 10.1029/2002JB002101.

Dehn, J., Dean, K., and Engle, K., 2000, Thermal monitoring of North Pacific volcanoes from space: Geology, v. 28, p. 755–758.

Energy Information Administration, 2001, State energy data report 1999 (consumption estimates): Washington, D.C., U.S. Department of Energy, 532 p.

Francis, P., Oppenheimer, C., and Stevenson, D., 1993, Endogenous growth of persistently active volcanoes: Nature, v. 366, p. 554–557.

Glaze, L., Francis, P.W., and Rothery, D.A., 1989, Measuring thermal budgets of active volcanoes by satellite remote sensing: Nature, v. 338, p. 144–146.

Harris, A.J.L., Flynn, L.P., Rothery, D.A., Oppenheimer, C., and Sherman, S.B., 1999, Mass flux measurements at active lava lakes: Implications for magma recycling: Journal of Geophysical Research, v. 104, p. 7117–7136.

Head, J.W., and Wilson, L., 1986, Volcanic processes and landforms on Venus: Theory, predictions, and observations: Journal of Geophysical Research, v. 91, p. 9407–9446.

Kaufman, Y.J., Justice, C.O., Flynn, L.P., Kendall, J.D., Prins, E.M., Giglio, L., Ward, D.E., Menzel, W.P., and Setzer, A.W., 1998, Potential global fire monitoring from EOS-MODIS: Journal of Geophysical Research, v. 103, p. 32,215–32,238.

Neri, A., 1998, A local heat transfer analysis of lava cooling in the atmosphere: Application to thermal diffusion-dominated lava flows: Journal of Volcanology and Geothermal Research, v. 81, p. 215–243.

Oppenheimer, C., and Francis, P., 1997, Remote sensing of heat, lava and fumarole emission from Erta 'Ale volcano, Ethiopia: International Journal of Remote Sensing, v. 18, p. 1661–1692.

Oppenheimer, C., and Yirgu, G., 2002, Thermal imaging of an active lava lake: Erta 'Ale volcano, Ethiopia: International Journal of Remote Sensing, v. 22, p. 4777–4782.

Oppenheimer, C., Francis, P.W., Rothery, D.A., Carlton, R.W.T., and Glaze, L.S., 1993, Infrared image analysis of volcanic thermal features: Lascar volcano, Chile, 1984–1992: Journal of Geophysical Research, v. 98, p. 4269–4286.

Pyle, D.M., 2000, Sizes of volcanic eruptions, *in* Sigurdsson, H., et al., eds., Encyclopedia of volcanoes: San Diego, Academic Press, p. 263–269.

Rose, W.I., 1987, Volcanic activity at Santiaguito volcano, 1976–1984: Geological Society of America Bulletin, v. 212, p. 17–27.

Simkin, T., and Siebert, L., 2000, Earth's volcanoes and eruptions: An overview, *in* Sigurdsson, H., et al., eds., Encyclopedia of volcanoes: San Diego, Academic Press, p. 249–261.

Watts, R.B., Herd, R.A., Sparks, R.S.J., and Young, S.R., 2002, Growth patterns and emplacement of the andesitic lava dome at Soufrière Hills volcano, Montserrat, *in* Druitt, T.H., and Kokelaar, B.P., eds., The eruption of Soufrière Hills volcano, Montserrat, from 1995 to 1999: Geological Society [London] Memoir 21, p. 115–152.

Wooster, M.J., Wright, R., Rothery, D.A., and Blake, S., 1997, Cooling mechanisms and an approximate thermal budget for the 1991–1993 Mount Etna lava flow: Geophysical Research Letters, v. 24, p. 3277–3280.

Wright, R., De La Cruz-Reyna, S., Harris, A., Flynn, L., and Gomez-Palacios, J.-J., 2002a, Infrared satellite monitoring of Popocatépetl: Explosions, exhalations, and cycles of dome growth: Journal of Geophysical Research, v. 107, no. B8, doi: 10.1029/2000JB000125.

Wright, R., Flynn, L.P., Garbeil, H., Harris, A.J.L., and Pilger, E., 2002b, Automated volcanic eruption detection using MODIS: Remote Sensing of Environment, v. 82, p. 135–155.

Manuscript received 13 October 2003
Revised manuscript received 24 November 2003
Manuscript accepted 26 November 2003

Printed in USA